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CROSS SECTION AND NEUTRON-YIELD FOR CHARGED PARTICLES INTERACTION WITH ^{66}ZN, ^{67}ZN, ^{103}RH AND ^{100}RU

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ABSTRACT

In this study reacting charged particles with intermediate nucleus as a target (^{67}Zn , ^{103}Rh, ^{66}Zn *and* ^{100}Ru) in $^{67}_{31}Zn(p,n)^{67}_{32}Ga$, $^{103}_{45}Rh(p,n)^{103}_{46}Pd$, $^{66}_{30}Zn(d,n)^{67}_{31}Ga$, $^{100}_{44}Ru(\alpha,n)^{103}_{46}Pd$ reactions as well as proton with range energy (4-29.5MeV) for $^{67}_{31}Zn(p,n)^{67}_{32}Ga$ reaction, proton with range energy (2.305-39.055MeV) for $^{103}_{45}Rh(p,n)^{103}_{46}Pd$, deuteron with range energy (1.8-15.4MeV) for $^{66}_{30}Zn(d,n)^{67}_{31}Ga$ and alpha particle with range energy (10.0-25.0 MeV) for $^{100}_{44}Ru(\alpha,n)^{103}_{46}Pd$ are used according to the available experimental data of cross sections in Exfor library.

We've calculated the cross section of above mentioned data and results have been obtained by using (Matlab-8.34014a) program.

The stopping powers have been calculated from Zeigler formula by using SRIM-2013 with the results of cross sections to calculate the neutron-yield for reactions depending on ^{67}Zn, ^{66}Zn, ^{103}Rh and ^{100}Ru isotopes as targets for reactions, and also comparing between cross section of those reactions to choose the best reactions to produce ^{67}Ga *and* ^{103}Pd isotope as shown in figure (5) and (7). We also found that comparing between neutron yields of mentioned reactions to choose the best reaction which has high neutron yield as shown in figure (6) and (8).

KEYWORDS: Cross Section (Excitation Function), Stopping Power, Neutron Yield, Data Evaluation, Gallium-67, Palladium-103

INTRODUCTION

The study of nuclear reactions of charged particles (*p, d, α*) with intermediate nucleus as a target which has a high neutron yield due to the advantages of the (*p,n*), (*d,n*), (*α,n*) neutron source and to produce radioisotopes as Gallium-67 and Palladium-103. They are very important because it provides a basis for a wide range of technical applications, Particularly using the reactions induced by intermediate energy protons, it is possible to produce directly radionuclides which have been used in medicine and industry, recent decades, where widespread uses of diagnostic and therapeutic radioisotopes take place. Depending on the type of radiation, the diagnostic isotopes are classified into two groups: β^+, β^- emitters (^{13}N, ^{15}O, ^{18}F, ^{62}Cu, ^{68}Ga, etc.) used in Positron Emission Tomography (PET), and γ-emitters (^{67}Ga, ^{99m}Tc, ^{123}I, etc.) used in Single Photon Emission Computed Tomography (SPECT).

The total cross section of such a production is also important in accelerator technology from the point of view for radiation protection safety [1].

Gallium-67 is used for tumor imaging and localization of inflammatory lesions (infections) [2]. Gallium-67 behaves in the body in a similar way to ferric iron. It is commonly used as a trivalent citrate compound for nuclear medicine imaging, and is a valuable agent in the detection and localization of certain neoplasms and inflammatory lesions [3]. Gallium-67 with a half life of ($T_{1/2}$=3.217 d), its decays to stable ^{67}Zn by electron capture. Its decay emissions include gamma rays of 93.3 keV (37.0%), 184.6 keV (20.4%) and 300.2 keV (16.6%). is a cyclotron-produced radioisotope for which considerable demand exists [3]. This radioisotope ^{67}Ga is well known and widely used in the field of nuclear medicine. ^{67}Ga has become one of the most frequently employed cyclotron produced radioisotope over the last two decades and is a widely used single photon marker for detecting the presence of malignancy and for diagnosing inflammatory lesions [4].

Palladium-103 is used to make sealed seeds (brachytherapy) as a permanent implant seeds for early stage prostate cancer [2]. Palladium-103 is extensively used in the treatment of prostate cancer as well as in ocular melanoma, and is mostly applied in the form of sealed seeds (brachytherapy) [4]. Palladium-103 has a suitable half-life of ($T_{1/2}$=16.991 d), its decays to stable ^{103}Rh by electron capture 100 %. which de-excites by means of a heavily converted internal transition. as a result of both processes (EC and IT), X-rays and Auger electrons are both emitted which are ideally suited for brachytherapy (its electron capture decay resulting in abundant emission of Auger electrons and low energy X-rays (20–22 keV)) [3,5].

NUCLEAR REACTION

The *Q*-value of the X(a,b)Y reaction is defined as the difference between the final and initial kinetic energies and is given by [6,7,8]:

$$Q = \left[M_a + M_X - \left(M_b + M_Y\right)\right] \times 931.5 \tag{1}$$

The threshold energy for a nuclear reaction is defined as the smallest value of a projectile's kinetic energy at which a nuclear reaction can take place [8, 9].

$$E_{th} = -Q\left(1 + \frac{M_a}{M_X}\right) \tag{2}$$

NUCLEAR CROSS SECTIONS

To study nuclear reactions, it is necessary to have a quantitative measure of the probability of a given nuclear reaction. In which the cross section of nuclides is the effective area presented [10]. When an accelerated charged particle interacts with a target nucleus a nuclear reaction takes place, ultimately leading to a stable or radioactive product nucleus. A nuclear reaction is characterized by a cross-section, describing the probability that a particle interacts [9, 11]. The cross section has the units of area as it's the square of nuclear radius. The standard unit for measuring a nuclear cross section (σ) is the barn (b), which is equal to (1barn=10^{-24} cm²) or (1barn=10^{-28} m²). The reaction cross section data provides information of fundamental importance in the study of nuclear systems. The cross section is defined by [12]:

$$\sigma = \frac{R}{I} \tag{3}$$

Were R is the number of reactions per unit time per nucleus. I is the number of incident particles per unit time per unit area, In general, a given bombarding particle and target can react in a variety of ways producing a variety of light reaction products per unit time. The total cross section is than defined as [8]:

$$\sigma_{total} = \sum \sigma_i \tag{4}$$

Where σ_i is the partial cross section for the process.

STOPPING POWER

The energy of charged particle loses per unit path length of the material it traverses. Generally speaking, any charged particle can have either electronic, nuclear, or gravitational interaction with the particles of the material through which it passes. However the gravitational interaction is too low to be of any significance and is generally ignored. The total stopping power is then just the sum of the stopping powers due to electronic and nuclear interactions [13,14,15].

$$-\frac{dE}{dx} = S_{total} = S_{electronic} + S_{nuclear} \tag{5}$$

Where $S_{electronic}$ is the electronic stopping power, $S_{nuclear}$ is the nuclear stopping power. The electronic stopping power is always much larger than the nuclear stopping power. For most practical purposes the nuclear component of the stopping power can also be ignored as it is generally only a fraction of the total stopping power. For particles such as electrons, this statement is always valid since they are not affected at all by the strong nuclear force.

Electronic Stopping

Electronic Stopping Power (S_e) The beam particles hitting a target get slowed down by interactions with the electrons until they are in thermal equilibrium with their surroundings. As a consequence one gets a wide neutron spectrum if the projectiles are completely stopped in the target, even if all nuclear reactions were two-body reactions. The loss of kinetic energy in a nuclear encounter would be much larger [7]. In the scope of this work, the electronic stopping powers were calculated using the Ziegler formulae [15]. Reliable data are available for many elements over a wide range of energies. However, in order to obtain values for all elements over a continuous range of proton energies, the authors fit curves through the available experimental data to generate coefficients for use in a semi-empirical parameterization of the stopping power as a function of proton energy E (keV) and the target atomic number Z_2. S_e is assumed to be proportional to $E^{0.45}$ for $E < 25$ keV, except for $Z_2 \leq 6$, where it is proportional to $E^{0.25}$, for 25 keV $\leq E \leq$ 10 MeV [16,17].

$$\left(\frac{1}{S_e}\right) = \left(\frac{1}{S_{Low}}\right) + \left(\frac{1}{S_{High}}\right) \tag{6}$$

S_{Low} (Low energy stopping) is

$$S_{Low} = A_1 E^{A_2} + A_3 E^{A_4} \tag{7}$$

S_{High} (High energy stopping) is

$$S_{High} = \frac{A_5 \ln(\frac{A_6}{E} + A_7 E)}{E^{A_6}} \tag{8}$$

Where E (KeV) energy of proton and the coefficients A_i for each Z_2, available from SRIM [16, 18]

For 10 MeV ≤ E ≤ 2 GeV,

$$S_{High} = A_9 + A_{10}(\frac{\ln E}{E}) + A_{11}(\frac{\ln E}{E})^2 + A_{12}(\frac{E}{\ln E}) \tag{9}$$

For use in the parameterization Proton stopping, $S_t(^1H)$, in various target materials for 10 kev ≤ E ≤ 100 MeV, High-energy proton stopping Se ~St, Proton stopping power for 1 kev ≤ E ≤ 10 GeV and $Z_2 \leq 92$, based on a combination of theoretical calculations and experimental data (for 20 keV ≤ E ≤ 1 MeV) [18,19].

Nuclear Stopping Power (S_n)

A beam of charged particles bombarding the neutral atoms of a target interacts with the atomic nuclei and atomic electrons of the target. The ratio of the energy lost in interaction with the atomic electrons, to the energy lost in the interaction with the atomic nuclei [14]

$2m_p / m_e \cong 4x10^3$

Thus the energy lost by interaction with the nuclei is negligible compared with that lost by interaction with the electrons. for solid targets with a given thickness there will be the more nuclear interactions and hence the electronic stopping cross sections is comparable with the nuclear cross section [15]. the theory of ion-solid interactions is well established and it has been discussed in detail [18,20]. Where the authors also described the computer program SRIM [16,18]. which can be used for calculating stopping power and range for ion/target combinations with Z≤92.

For sufficiently high projectile energies, $S_t \sim S_e$. S_n, in units of eV/10^{15} atoms/cm^2, for any projectile with energy E (kev), is given by [16,18].

$$S_n(E) = \frac{8.462\, Z_1 Z_2 M_1 S_n(\varepsilon)}{(M_1 + M_2)(Z_1^{0.23} + Z_2^{0.23})} \tag{10}$$

Where the reduced ion energy, ε, is defined as

$$\text{Reduced Ion Energy} = \varepsilon = \frac{32.53 M_1 M_2 (E / M_1)}{Z_1 Z_2 (M_1 + M_2)(Z_1^{0.23} + Z_2^{0.23})} \tag{11}$$

Where M_1 and M_2 are the projectile and target masses (amu), and Z_1 and Z_2 are the projectile and target atomic

numbers. For ε ≤ 30 keV,

$$S_n(\varepsilon) = \frac{\ln(1+1.1383\varepsilon)}{2(\varepsilon + 0.01321\varepsilon^{0.21226} + 0.19593\varepsilon^{0.5})} \quad (12)$$

For ε > 30 keV, unscreened nuclear stopping is used, and $S_n(\varepsilon)$ simplifies to

$$S_n(\varepsilon) = \frac{\ln \varepsilon}{2\varepsilon} \quad (13)$$

NEUTRON YIELDS

The neutron yield (Y_n) detected per incident particle (proton, deuteron alpha), for an ideal, thin, and uniform target and mono-energetic particles beam of incident energy E_b is given by [13].

$$Y_n = (N_d x)\sigma(E_b)\eta(E_b) \quad (14)$$

Where N_d is the a real number density of target atoms, x is the target thickness, σ is the reaction cross section and η is neutron detection efficiency. If the target is sufficiently thick, For a target which is not infinitesimally thin, the beam loses energy as it passes through the target, if the target is sufficiently thick, and there exist one atom per each molecule (i.e., f = 1) and taking (E`) = 1, then the resulting yield is called the thick-target yield which is given by [13,21,22].

$$Y_n(E_b) = N \int_{E_{th}}^{E_b} \frac{\sigma(E)}{dE/dx} dE \quad (15)$$

Where E_{thr} is the reaction threshold energy, σ(E) is the cross section, *dE/dX* is the incident particle initial energy, **N** is the atomic number of target per unit volume, which is defined as follows:

$$N = \frac{w \rho N_a}{A} \quad (16)$$

Where, *w* is the abundant in the combination, is the combination density, A is the mass number, N_A is the Avogadro's number.

Thus, by measuring the yield at two closely spaced energies (E1) and (E2), one can determine the average value of the integrand over this energy interval as follows [23]:

$$Y(E_2) - Y(E_1) = \left[\frac{\sigma(E)}{dE/dx}\right]_{E_b} (E2 - E1) \quad (17)$$

Where (*Eb*) is the average of (*E1*) and (*E2*). If *σ (E)* are available in the literature as a function of projectile energy (*Eb*) for natural elements, then the neutron yield can be calculated using eq.(13). If neutron yield is available as a function of projectile energy (*Eb*), then eq. (13) can be used to calculate *σ(E)* as a function of (*Eb*). Thus, consequently one can

calculated the neutron yield by using eq. (17), For natural elements and if only one stable isotope is available in nature, then [24]

$$Y_0 = Y(E) \quad (18)$$

Where (Yo) is the neutron yield per 10^6 bombarding particle for the natural element.

RESULTS AND DISCUSSIONS

The ${}^{67}_{31}Zn(p,n)\,{}^{67}_{32}Ga$ Reaction

The cross sections of the ${}^{67}_{31}Zn(p,n)\,{}^{67}_{32}Ga$ reaction have been published as a function of proton energy by Szelecsenyi [25], Hermanne [26], Levkovskij [27], Little [28] in Exfor library Accordingly we've used the range of energies above the threshold energy (1.8105MeV) with range of energy (4-29.5MeV) in step of (0.5 MeV), the cross section of ${}^{67}_{31}Zn(p,n)\,{}^{67}_{32}Ga$ reaction depends on the kinetic energy of the proton and directly proportional with the kinetic energy of proton until reaches to (11.0 MeV) which is the maximum value of the cross section (σ_{Max}=739.09 mb) after that it decreases with the increasing of kinetic energy of proton. The aim of study is for the cross section and neutron yield for reaction which is shown in figure (1) and (6) because this reaction is one of the important interactions that lead to the production of radioactive isotope such as ^{67}Ga.

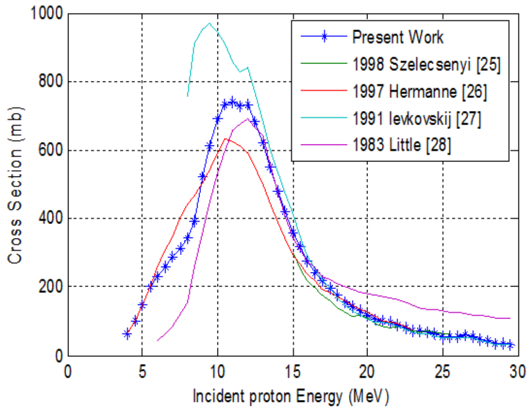

Figure 1: The Cross Sections of ${}^{67}_{31}Zn(p,n)\,{}^{67}_{32}Ga$

The ${}^{66}_{30}Zn(d,n)\,{}^{67}_{31}Ga$ Reaction

The cross sections of the ${}^{66}_{30}Zn(d,n)\,{}^{67}_{31}Ga$ reaction have been published as a function of deuteron energy by Williams [29] Accordingly the cross section is used within range of energy (1.8-15.4MeV) in step of (0.4 MeV), the cross section of ${}^{66}_{30}Zn(d,n)\,{}^{67}_{31}Ga$ reaction depends on the kinetic energy of the deuteron and directly proportional with the kinetic energy of deuteron until reaches to (8.2MeV) which is the maximum value of the cross section (σ_{Max}=422.22mb) after that decreases with the increasing of kinetic energy of deuteron. The aim of study is for the cross section and neutron yield of reaction which is shown in figure (2) and (6) because this reaction is one of the important interactions that lead to the production of nuclei radioactive such as ^{67}Ga.

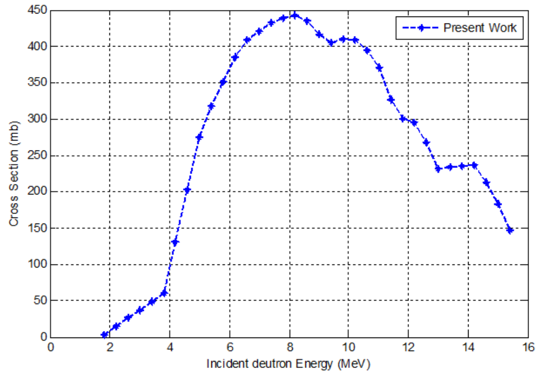

Figure 2: The Cross Sections of $^{66}_{30}Zn\,(d\,,n)\;^{67}_{31}Ga$

The $^{103}_{45}Rh\,(p\,,n)\;^{103}_{46}Pd$ Reaction

The cross sections of the $^{103}_{45}Rh\,(p\,,n)\;^{103}_{46}Pd$ reaction have been published as a function of proton energy by Sudar [30], Hermanne [31], Harper [32] , Johnson [33] in Exfor library, Accordingly we've used the range of energies above the threshold energy (1.3385MeV) with range of energy (2.305-39.055MeV) in step of (0.75MeV), the cross section of $^{103}_{45}Rh\,(p\,,n)\;^{103}_{46}Pd$ reaction depends on the kinetic energy of the proton and directly proportional with the kinetic energy of proton until reaches to (9.805MeV) which is the maximum value of the cross section (σ_{Max}=509.93 mb) after that it decreases with the increasing of kinetic energy of proton. The aim of study is for the cross section and neutron yield of reaction which is shown in figure (3) and (8) because this reaction is one of the important interactions that lead to the production of radioactive isotope such as Palladium-103.

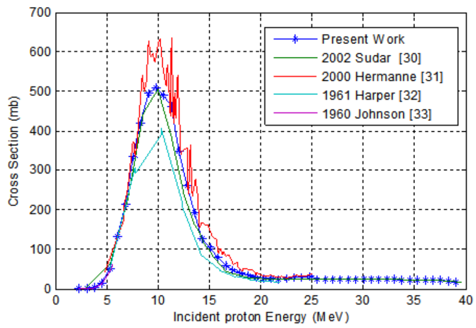

Figure 3: The Cross Sections of $^{103}_{45}Rh(p\,,n)\;^{103}_{46}Pd$

The $^{100}_{44}Ru\,(\alpha\,,n)\;^{103}_{46}Pd$ Reaction

The cross sections of the $^{100}_{44}Ru\,(\alpha\,,n)\;^{103}_{46}Pd$ reaction have been published as a function of proton energy by Qaim [34], Hussain [35] in Exfor library, Accordingly we 've used the range of energies above the threshold energy (7.6815MeV) with range of energy (1.8-15.4MeV) in step of (0.4 MeV),the cross section of $^{100}_{44}Ru\,(\alpha\,,n)\;^{103}_{46}Pd$ reaction depends on the kinetic energy of the alpha particle and directly proportional with the kinetic energy of proton until reaches to (19MeV) which is the maximum value of the cross section (σ_{Max}=526.55mb) after that it decreases with the increasing of

kinetic energy of alpha particle. The aim of study is for the cross section and neutron yield of reaction which is shown in figure (4) and (8) because this reaction is one of the important interactions that lead to the production of radioactive isotope such as Palladium-103.

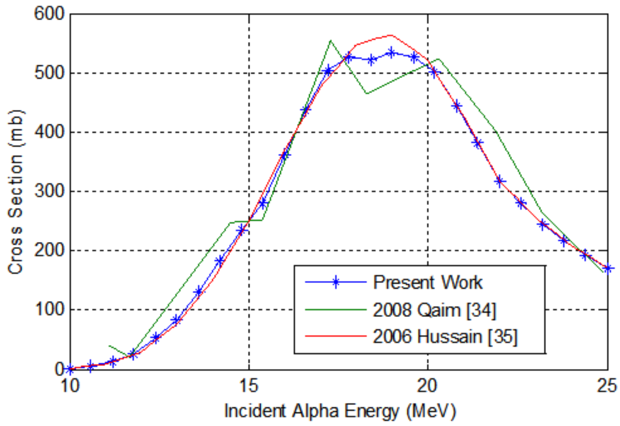

Figure 4: The Cross Sections $^{100}_{44}Ru(\alpha,n)\,^{103}_{46}Pd$

CONCLUSIONS

From the results of the cross sections and neutron yield for (p,n), (d,n), (alpha,n) reactions with many intermediate nucleus target and production of many radioisotopes with short half life we have been observed many conclusions for this study of (p,n), (d,n), (alpha,n) reactions.

- The main contribution process to produce ^{67}Ga radionuclide [$^{67}_{31}Zn(p,n)\,^{67}_{32}Ga$ and $^{66}_{30}Zn(d,n)\,^{67}_{31}Ga$ reactions] have a high cross section value. the maximum value of the cross section (σ_{Max}=739.09 mb) at kinetic energy of proton (11.0 MeV) for *(p,n)* reaction, while the maximum value of the cross section (σ_{Max}=422.22 mb) at kinetic energy of deuteron (8.2MeV) for *(d,n)* reaction illustrates in figure (5). the *(p,n)* reaction is the best to produce Gallium-67 because of the high cross section value compare with (d,n) reaction.

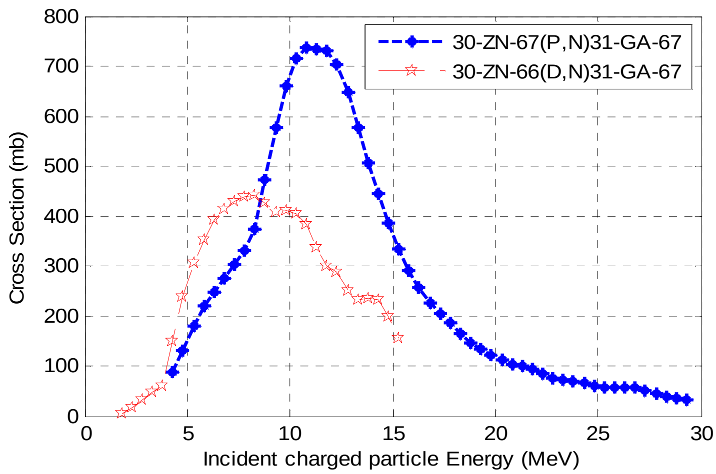

Figure 5: The Cross Sections For $^{67}_{31}Zn\,(p,n)\,^{67}_{32}Ga$ **and** $^{66}_{30}Zn(d,n)\,^{67}_{31}Ga$ **Reactions**

In figure (6) the $^{67}_{31}Zn\,(p\,,n)\,^{67}_{32}Ga$ reaction has neutron yield value a better than $^{66}_{30}Zn(d\,,n)\,^{67}_{31}Ga$ reaction because of the high cross section, lower stopping power of incident proton on nucleus target ^{67}Zn than incident deuteron on nucleus target ^{66}Zn with dependence on equation (17) as shown in figure (5), The *(p, n) as* neutron source with intermediate mass nuclei as a target is the best which has the high neutron yield compare with *(d,n)* reaction.

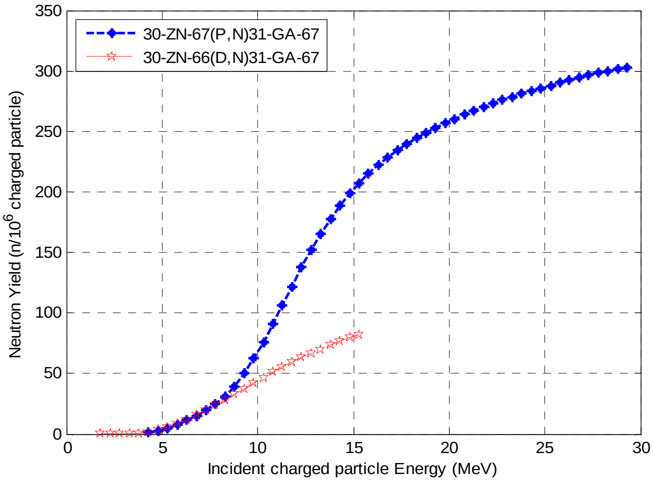

Figure 6: The Neutron Yield for $^{67}_{31}Zn\,(p\,,n)\,^{67}_{32}Ga$ and $^{66}_{30}Zn(d\,,n)\,^{67}_{31}Ga$ Reactions

The main contribution process to production ^{103}Pd radionuclide [$^{103}_{45}Rh(p\,,n)\,^{103}_{46}Pd$, $^{100}_{44}Ru\,(\alpha\,,n)\,^{103}_{46}Pd$ reactions] have a high cross section value. The maximum value of the cross section (σ_{Max}=509.93 mb) at kinetic energy of proton (9.805MeV) for *(p,n)* reaction, and the maximum value of the cross section (σ_{Max}=526.55mb) at kinetic energy of alpha particle (19MeV) for *(α,n)* reaction illustrates In figure (7). the *(p,n),(α,n)* reactions are best reactions to produce Palladium-103 but the *(p,n)* reaction is better than *(α,n)* reaction to produce palladium-103 because it has a high value of cross section at low energy (9.805MeV) while the *(α,n)* reaction has a high value of cross section as well at energy (19.9MeV).

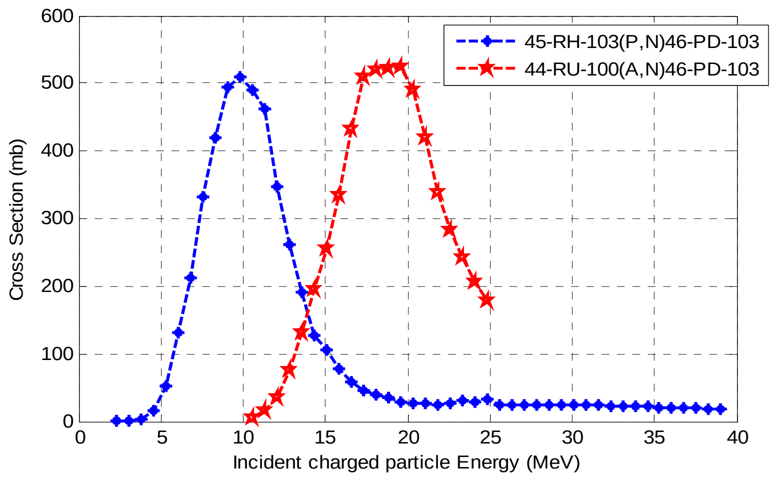

Figure 7: The Cross Sections for $^{103}_{45}Rh(p\,,n)\,^{103}_{46}Pd$ and $^{100}_{44}Ru(\alpha\,,n)\,^{103}_{46}Pd$ Reactions

For ${}^{103}_{45}Rh\,(p,n)\,{}^{103}_{46}Pd$, ${}^{100}_{44}Ru\,(\alpha,n)\,{}^{103}_{46}Pd$ reactions, the neutron yield of *(p,n)* reaction is higher value than *(α,n)* reaction as neutron source as it has a high cross section and low stopping power of incident proton, the neutron yield value dependence on equation (17) as illustrates in figure (8), The *(p, n) as* neutron source with intermediate mass nuclei as a target is the best which has the high neutron yield compare with *(α,n)* reaction..

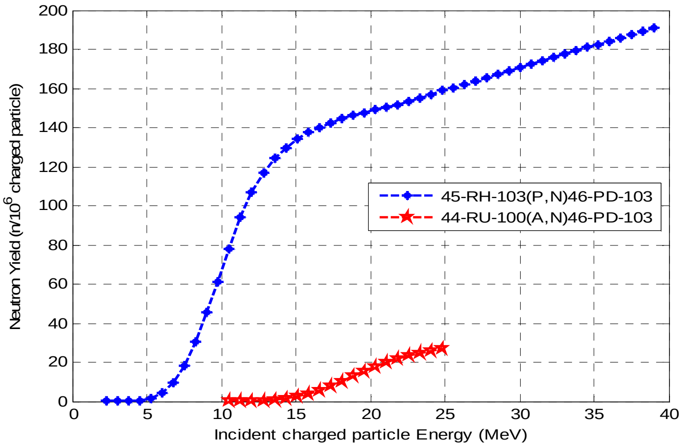

Figure 8: The Neutron Yield for ${}^{103}_{45}Rh(p,n)\,{}^{103}_{46}Pd$ and ${}^{100}_{44}Ru(\alpha,n)\,{}^{103}_{46}Pd$ Reactions

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